Overview of Muon Collider Rings, MDI and Background Mitigation

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Design Goals

Lattice design goals:

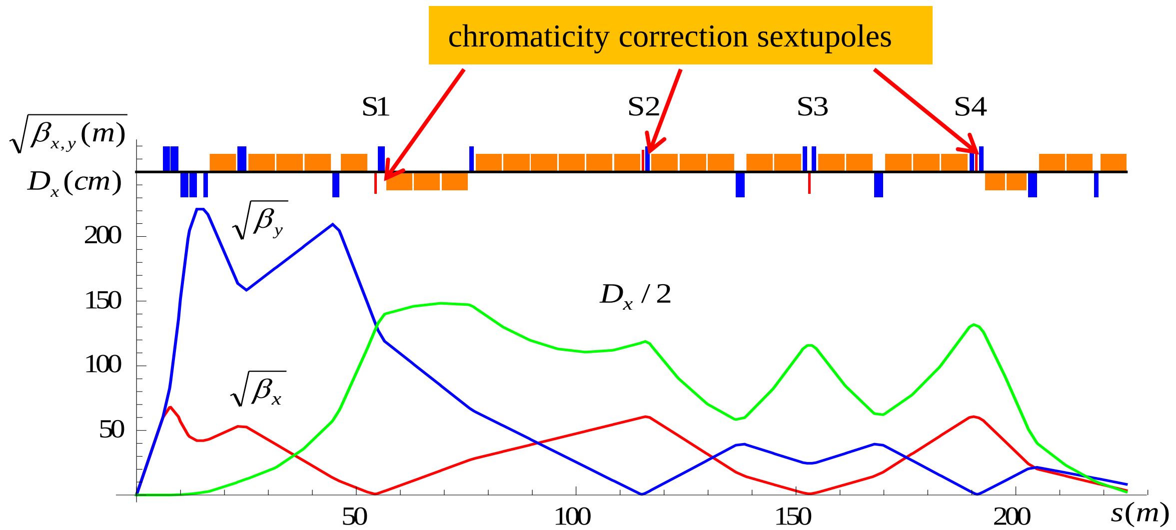
- High Luminosity (small β^*, circumference, momentum compaction)
- Acceptable detector backgrounds (tight apertures, dipole component in FF quads, halo suppression)
- Manageable heat loads in magnets (W absorbers and masks, shorter magnets, again dipole component in quads)
- β^* variation in wide range (w/o breaking dispersion closure)
- Limited β_{max} to reduce required apertures and sensitivity to errors.
- Higgs Factory: small collision energy spread $\sigma_E/E \leq 4{\cdot}10^{-5}$
- High Energy MC ($E_{com} \geq$ 3TeV): safe levels of ν-induced radiation (no long straights, combined-function magnets to spread ν's)

Magnet design goals:

- High nominal fields in the required (large) aperture
- Sufficient operation margin to work at high dynamic heat load
- Accelerator beam quality in the beam area
- Not just theoretical feasibility, but also technological realizability (stress management, cooling, quench protection, protection from radiation, production process!)

E_{com}=1.5 TeV Collider Lattice

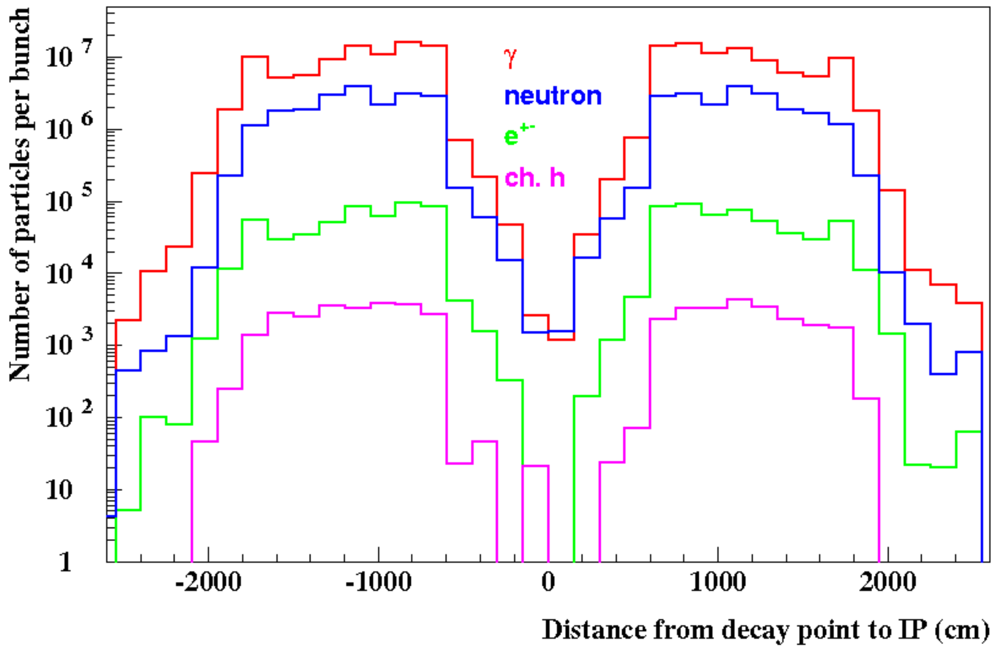
β*=1cm



This was chronologically the first successful design (November 2009) for which an (almost) full cycle of studies was completed:

- 3-sextupole chromaticity correction scheme developed → stable momentum range ± 1.2%, DA > 4σ w/o errors
- Magnet design for entire ring (10T pole tip field assumed)
- Heat deposition and detector background simulations → important conclusions (see next slides), the background level achieved ~ that at LHC
- Study of systematic field errors (fringe fields and multipoles) and attempt to correct them (finished with DA ≈ 3σ due to open-midplane magnet multipoles)
- Study of beam-beam effects (including strong-strong)

Background Source Tagging for 1.5 TeV MC



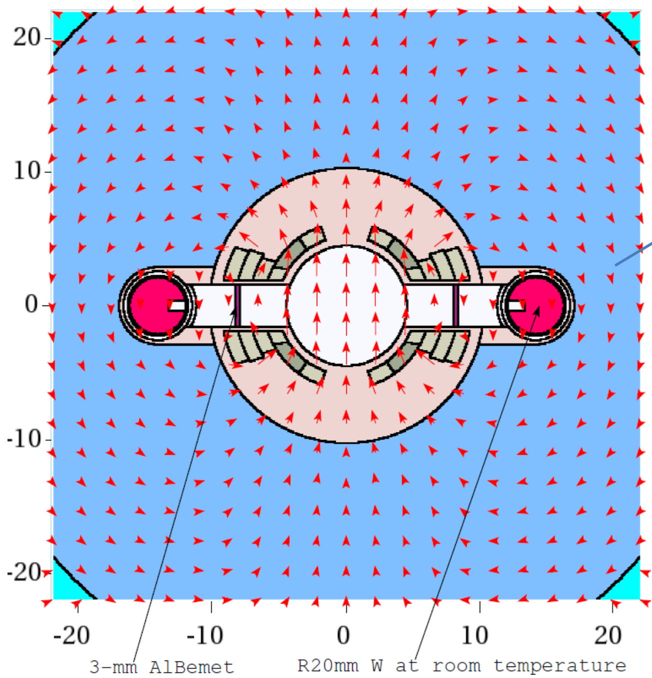
For BH muons the origin within ±100m

All background species (except BH muons) originate from region ±18m w/o strong dipole field (though there is 2T in defocusing quads).

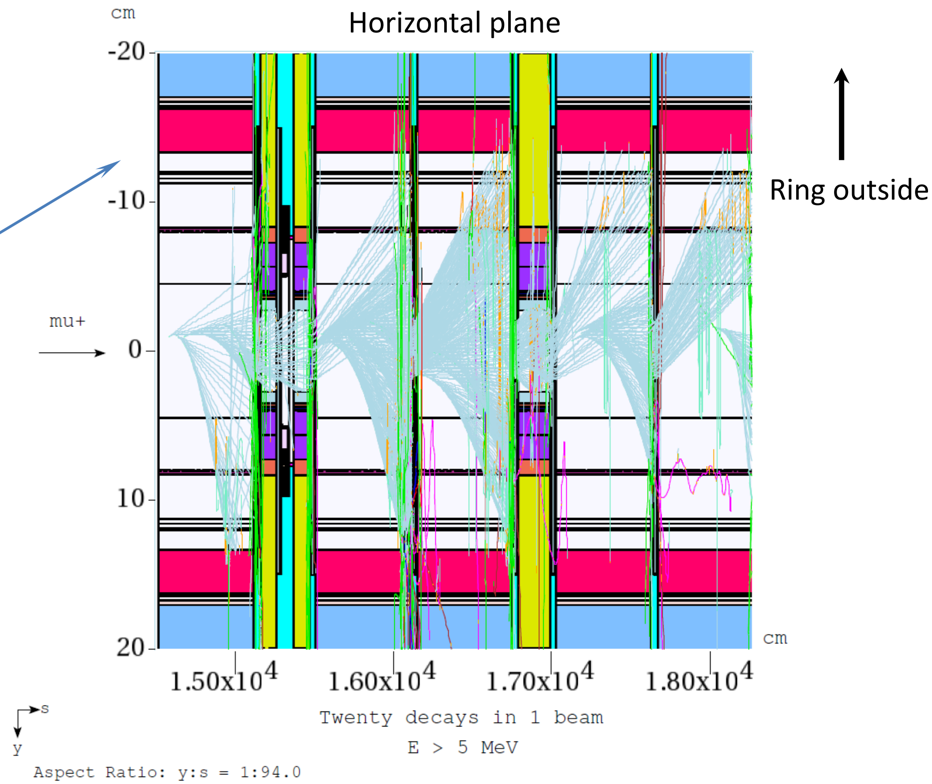
This result settles the discussion if a dipole field in the detector vicinity is a good or a bad thing – it is needed!

The subsequent designs for Higgs Factory and 3 TeV collider employed quadruplet Final Focus with 2T dipole field in the 2^{nd} from IP quad (see support slides for detail)

Showers from μ+ Decays in CC Section



Open-midplane dipole



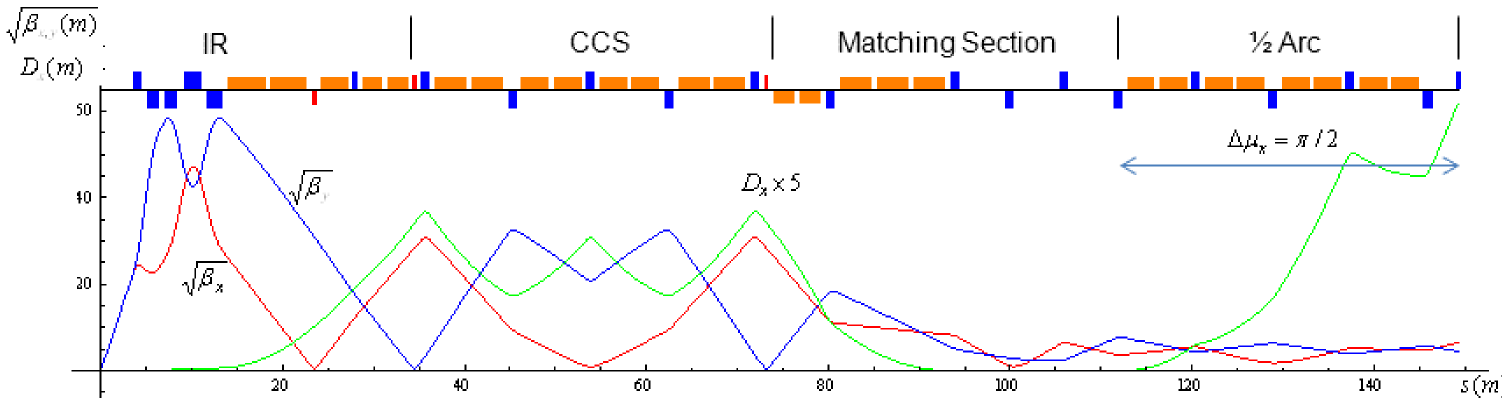
- Energy deposition in quads may exceed Nb_3Sn quench limit due to "punch through" the masks from midplane gaps in dipoles
- Decay electrons linger at field-reversal radial position in dipoles and eventually hit vertically the cold mass, not the rods

Open-midplane dipoles do not work

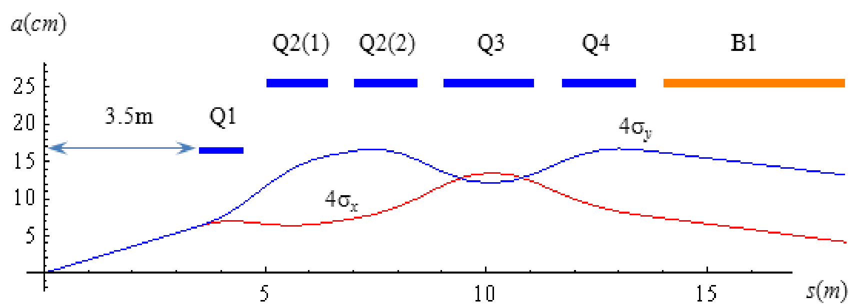
- Electrons are spread by quadrupoles $\rightarrow$ synchrotron γ's hit elements on the outside of dipoles

Combined-function magnets can be helpful

Higgs Factory Lattice

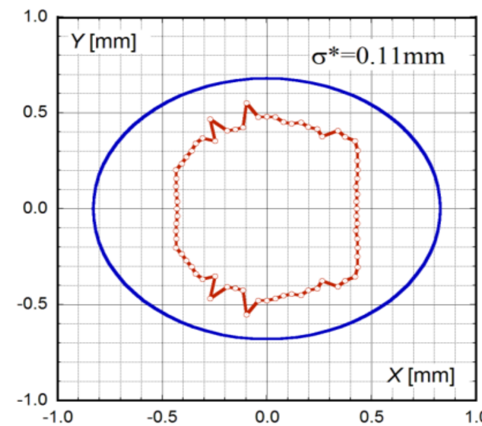


Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP



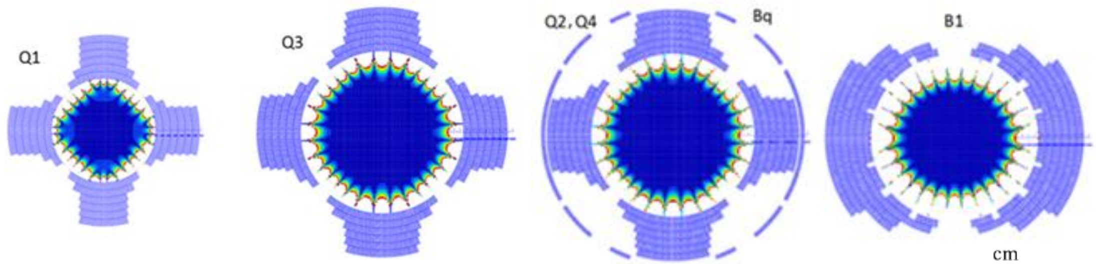
IR quad cold mass inner radii and 4σ beam envelopes for β*=2.5cm.
Q2 and Q4 have 2T dipole component (need higher?)

Very large magnet aperture required due to high transverse emittance → fringe fields !

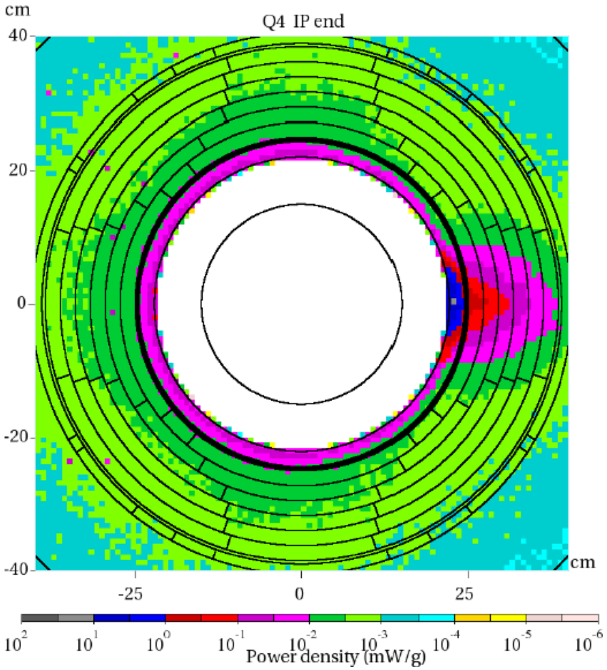


The dynamic aperture (fringe fields + multipoles + correction on) and projection of FF quad aperture (solid ellipse).

Large Aperture Magnet Design

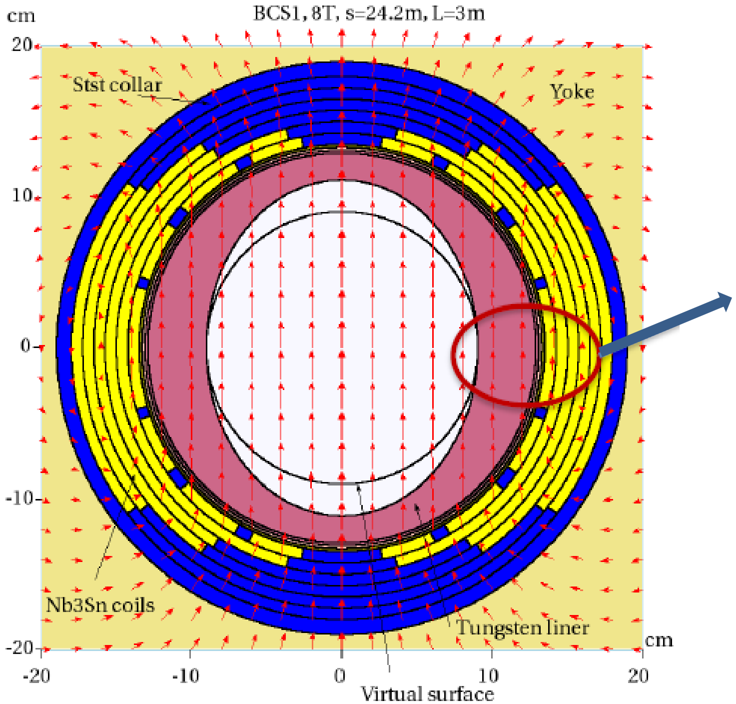


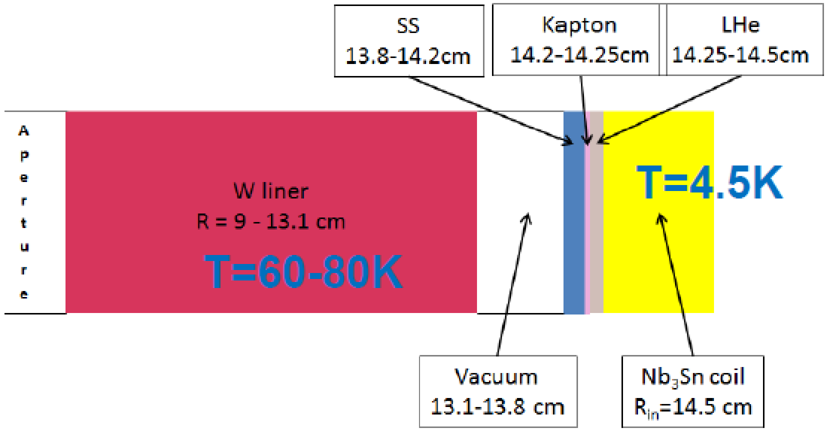
	Q1	Q2	Q3	Q4
aperture (cm)	32	50	50	50
gradient (T/m)	74	-36	44	-25
dipole field (T)	0	2	0	2
length (m)	1.0	1.4	2.05	1.7
B_{coil} (T)	16.4	17.2	16.9	(17.2)
Margin @ 4.5°K	0.78	0.62	0.70	(0.62)

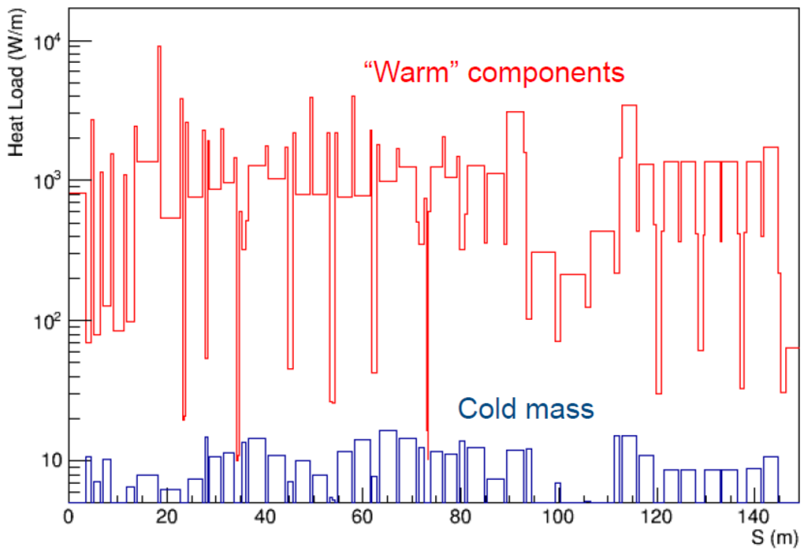


- 6-layer, shell-type coil design achieves the design goals with sufficient margin
- Good field quality region (deep blue) ~0.7 of the aperture determines the DA
- Masks between the quads at 4σ and inner absorbers reduced heat loads from 100-150mW/g to <1.5mW/g

Dynamic Heat Load





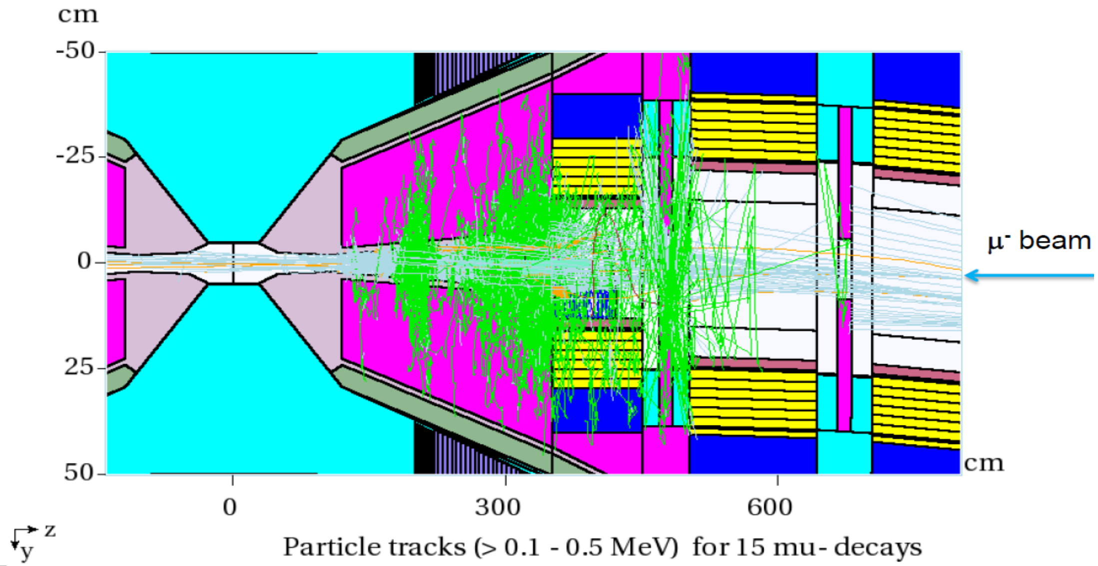


- Due to smaller circumference and higher muon flux the heat load in HF of ~1kW/m is twice higher than in high-energy MC
- With W masks optimized individually for each magnet interconnect region and with elaborate inner absorbers (top) the cold mass heat load was reduced to safe value ~10W/m

Higgs Factory Detector Backgrounds

Expect poorer performance compared to 1.5 TeV MC:

- geometrically larger aperture,
- almost twice shorter, substantially thinner cone,
- 2.5 times shorter trap and
- 3.5 longer tip-to-tip open region ($\pm 2\sigma_z$ plus no extra shadowing for collision products)

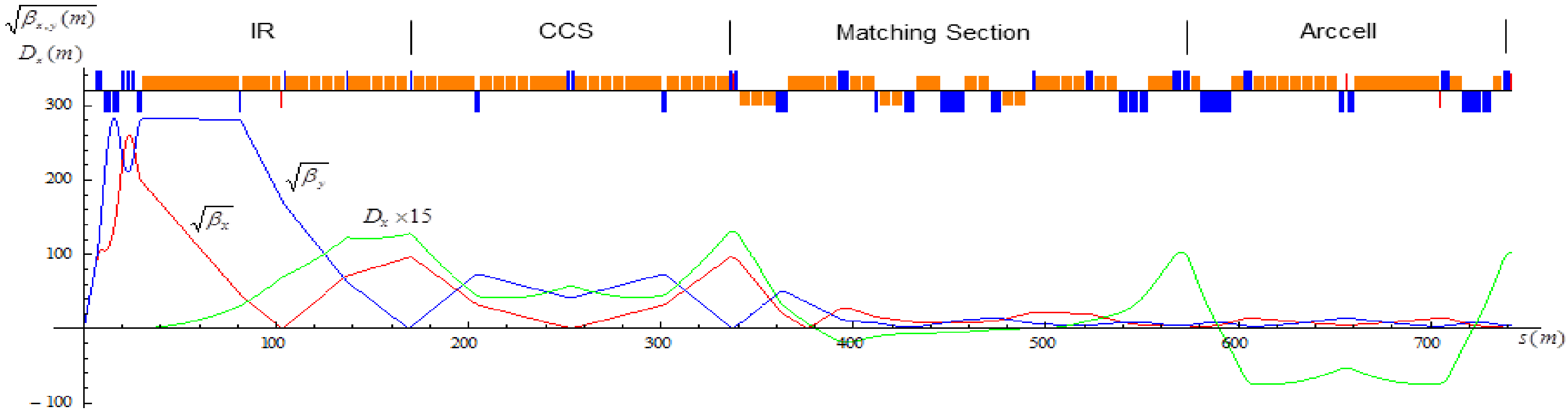


Particle tracks (> 0.1 - 0.5 MeV) for 15 mu- decays

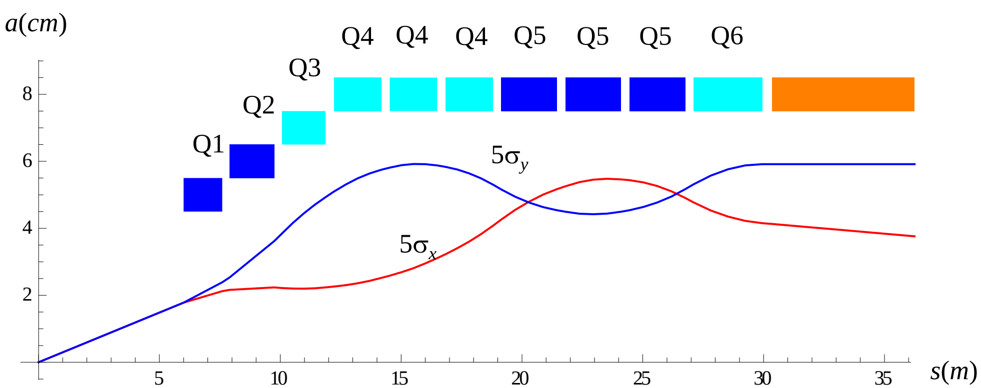
Particle		1.5-TeV MC 10deg	125-GeV HF V2 (MAP13 06/13)	125-GeV HF V7x2s4 (Jan. 2014)
Photon	N	1.8×10^8	3.2×10^9	2.8×10^8
	E	160 <E>=0.9 MeV	12000	2200 <E>=8 MeV
Electron	N	1.0×10^6	1.2×10^8	~1/50 → 2.0×10^6
	E	5.8 <E>=6 MeV	9000	32 <E>=16 MeV
Neutron	N	4.1×10^7	1.7×10^8	5.2×10^7
	E	170	300	86
Ch. Hadron	N	4.8×10^4	1.0×10^5	1.0×10^4
	E	12	26	2.3
Muon	N	8.0×10^3		2.8×10^3
	E	184 <E>=23 GeV		8.2 <E>=3 GeV

This number is challenged by Tom Markiewicz. Is the same shielding geometry, energy cuts etc. used?

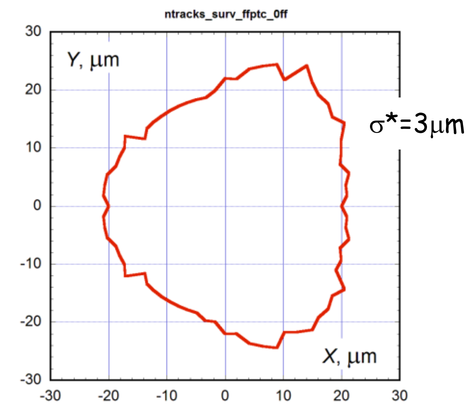
E_{com}=3TeV Collider Lattice



Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

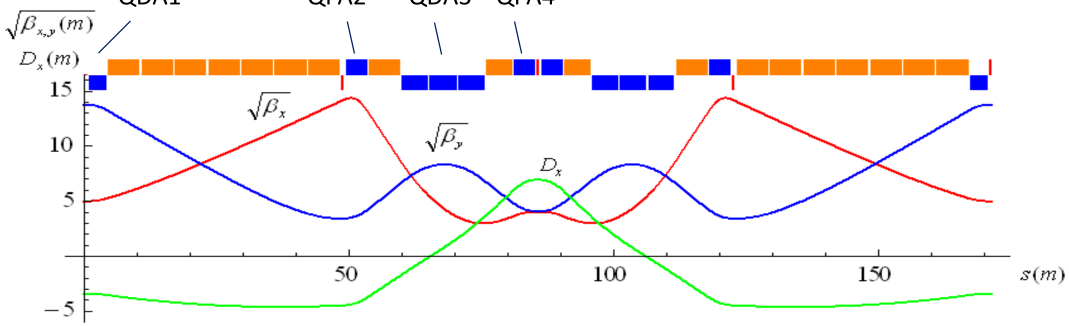


5 sigma beam sizes and magnet inner radii.
Q3, Q4 and Q6 have 2T dipole component.
$B_{\text{pole tip}}$= 12T for shown apertures, can be reduced to 10T – we do not need 5σ for the beam scraped at 3σ.



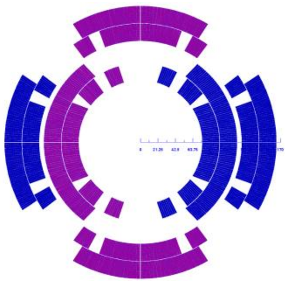
The dynamic aperture w/o field errors ≈6σ. The stable momentum range ±0.7%

Combined Function Magnets for the Arcs

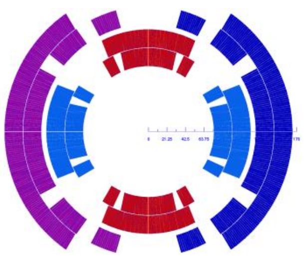


Motivation:

- Spread decay ν's
- Sweep away decay electrons before they depart from median plane – allows for azimuthally tapered absorber



Dipole/Quad



Quad/Dipole

Parameter (4.5K)	D/Q QDA1/3	Q/D	
		QDA1/3	QFA2/4
Maximum field in coil (T)	16.8/16.7*	16.5/17.5	
Maximum field or gradient in aperture (T or T/m)	9.3/76.7	12.0/72.5	
Operating field or gradient (T or T/m)	9.0/35.0	9.0/35.0	8.0/85.0
Fraction of SSL at the operating field	0.75/0.61*	0.70/0.64	0.75/0.86
Inductance L_{self} (mH/m)	16.0/20.6*	44.2/6.9	
Stored energy E at the operating field (MJ/m)	1.5/0.5	2.9/0.1	2.3/0.6
Horizontal Lorentz force F_x at the operating field (MN/m)	7.7/-0.1#	7.2/2.2	6.1/5.5
Vertical Lorentz force F_y at the operating field (MN/m)	-4.5/-1.6	-4.0/-0.3	-4.5/-1.5
Length (m)	3.34/5.0	3.34/5.0	1.8/2.8
Aperture (mm)	150	150	150

* the first value is for dipole coils, the second one is for quadrupole coils;
# totals per quadrant in dipole and per octant in quadrupole.

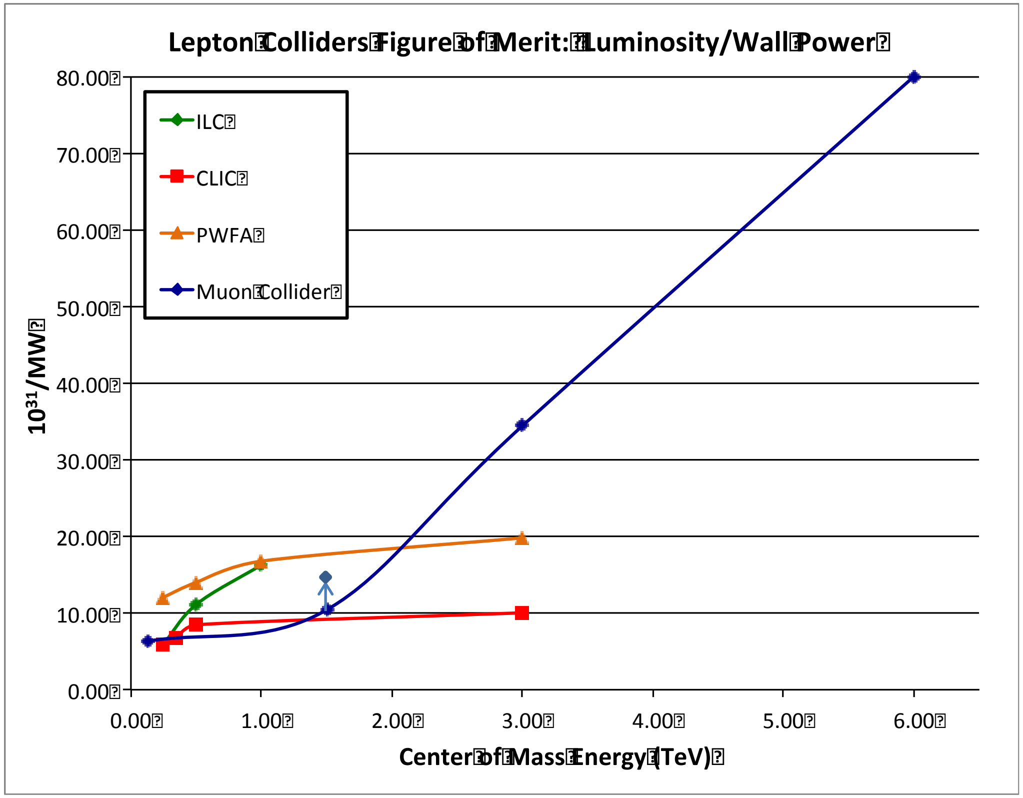
- Quad/Dipole design appears superior
- Preliminary analysis shows heat deposition in coils < 1.5 mW/g with only 2cm thick absorbers. However a thicker absorber can be required to keep the heat load below 10W/m

Design Parameters

Muon Collider parameters				
Collision energy, TeV	0.126	1.5	3.0	6.0*
Repetition rate, Hz	30	15	12	6
Average luminosity / IP, 10^{34}/cm^2/s	0.0025	1.25	4.6	13
Number of IPs	1	2	2	2
Circumference, km	0.3	2.5	4.34	6
β^*, cm	2.5	1	0.5	0.25
Momentum compaction factor	0.08	$-1.3\cdot10^{-5}$	$-0.9\cdot10^{-5}$	$-0.5\cdot10^{-5}$
Normalized emittance, $\pi\cdot$mm$\cdot$mrad	300	25	25	25
Momentum spread, %	0.003	0.1	0.1	0.1
Bunch length, cm	5.6	1	0.5	0.25
Number of muons / bunch, 10^{12}	2	2	2	2
Number of bunches / beam	1	1	1	1
Beam-beam parameter / IP	0.007	0.09	0.09	0.09
RF frequency, GHz	0.2	1.3	1.3	1.3
RF voltage, MV	0.1	12	85	530
Proton driver power (MW)	4	4	4	2

First attempt made by M.-H. Wang (SLAC), requires stronger magnets to keep *L~E^2*

Luminosity / Wall Power Comparison



1.5 TeV design used doublet FF, with quadruplet FF β* can be maid smaller and luminosity ~50% higher

Design Status

E_{com}(TeV)	Lattice design	Magnet design	Heat deposit.	MDI design	Magnet error corr.	Beam-beam & coherent
0.126	✓	✓	✓	✓	✓	✓
1.5	✓	✓	✓	✓	✓	✓
3.0	✓	✓	✓	–	–	–
6.0	–	–	–	–	–	–

If work on the Muon Collider will be resumed:

- Finish the 3TeV MC design (improve β^*-tuning section, design MDI, address beam collimation/halo extraction problem)
- Study tolerances on random field errors and misalignments – of general importance for understanding the real constraints on beta-functions, momentum compaction factor etc.
- Try larger dipole component in IR quads to reduce backgrounds
- Develop cryostat concept integrated with W absorbers and masks
- Start 6TeV lattice – with stronger HTS + LTS magnets (?)
- Re-design 1.5 TeV MC with quadruplet FF – if there is physics within its reach

Very High-Energy MC Prospects

Higher magnetic fields (and gradients) are the key to high luminosity:

- Circumference
- β^*

From A. Zlobin's talk at the previous MAP meeting:

Higher field magnets – *outside of the MAP scope and resources => GARD*

15 T Nb_3Sn magnets with coil ID~20(40) cm, B_{des}~18 T – *new class of Nb_3Sn accelerator magnets*

20 T HTS/LTS magnets (10 T HTS insert) with ~20 cm bore, B_{des}>25 T – *new magnet technology*

significant R&D effort is needed!!!

But we need <u>now</u> an educated guess of what will be feasible within 20 years

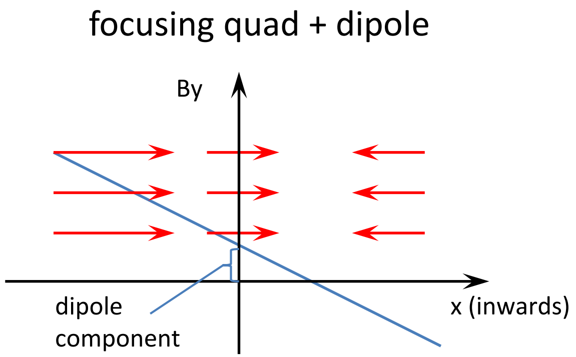
Achievements

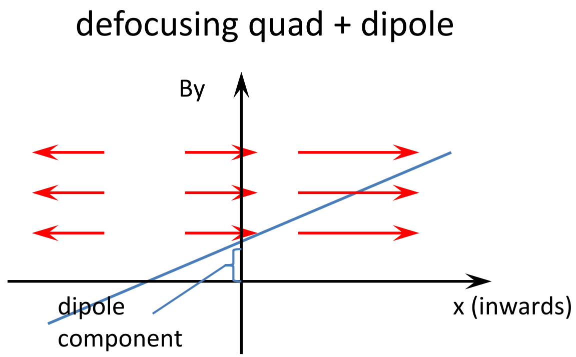
Concepts developed in the course of work on HF, 1.5TeV and 3TeV MC:

- 3-sextupole chromaticity correction scheme
- Quadruplet Final Focus (not implemented in the chronologically first 1.5TeV design)
- New Flexible Momentum Compaction arccell design (High Energy MC)
- β*-tuning section with a chicane (for $E_{com} \geq 3$TeV)

- Dipole component in IR quad is proven to reduce backgrounds
- Nozzle, cone, masks optimization Backgrounds in 1.5TeV MC (and in HF?) on par with LHC
- Classical cos-theta dipole with inner absorbers found superior to open-midplane
- Magnet studies for 0.125, 1.5 and 3 TeV MC are almost complete, apertures as large as 0.5m do not pose a problem
- Optimum configuration for combine-function magnets – a nested Quadrupole/Dipole magnet – found

Support slide - Why Quadruplet Final Focus?





- Dipole component in a defocusing quad is more efficient for cleaning purposes – it is beneficial to have the 2nd from IP quad defocusing
- The last quad of the FF “telescope” also must be defocusing to limit the dispersion “invariant” generated by the subsequent dipole (not shown)

$$J_x = \frac{D_x^2 + (\beta_x D_x' + \alpha_x D_x)^2}{\beta_x} \approx \beta_x \phi^2$$

– both requirement are met with either doublet or quadrupole FF: